The potential of collective Thomson scattering measurements in burning-plasma devices

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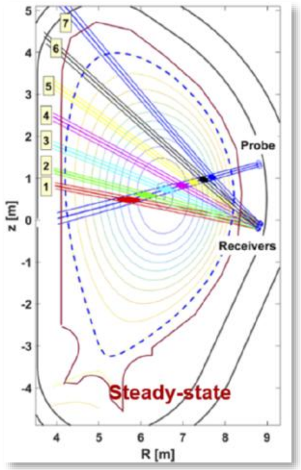

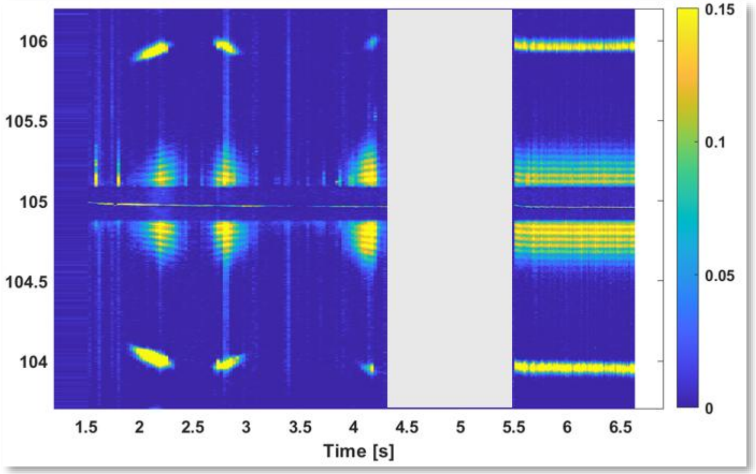

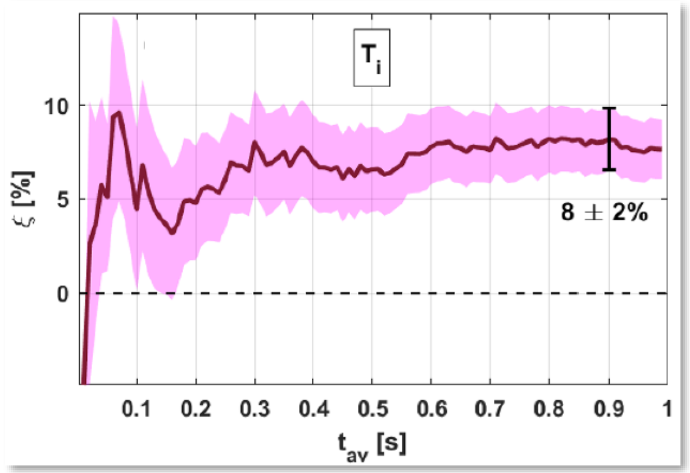

EUROfusion

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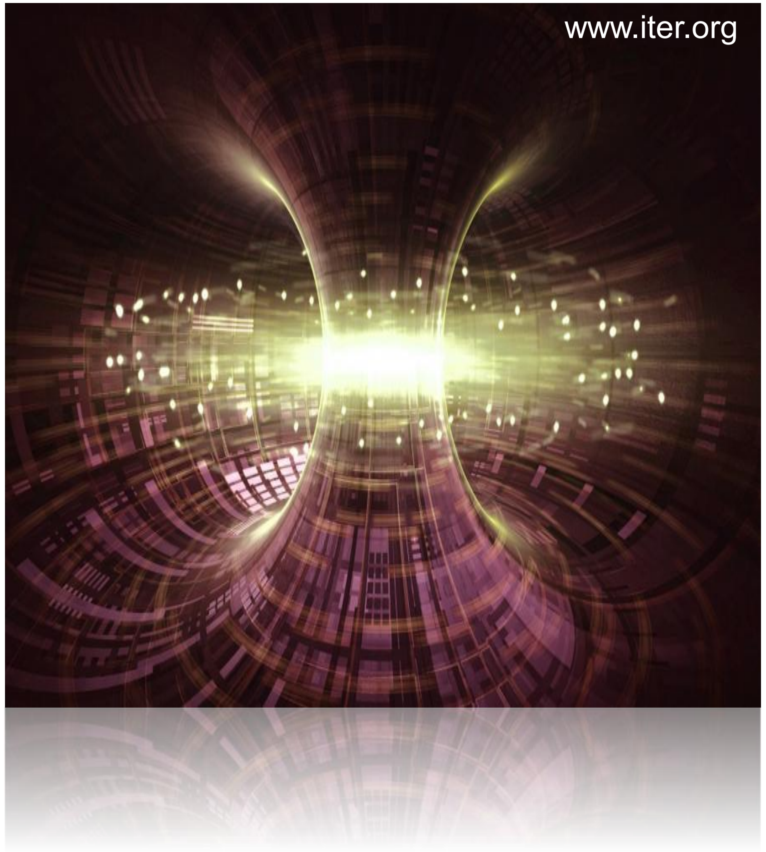
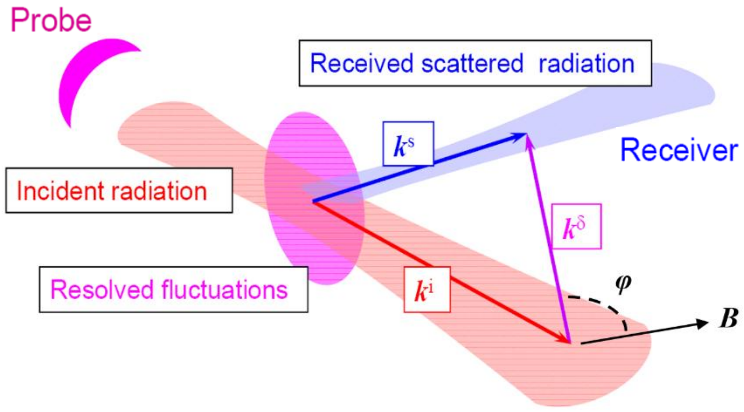
Outline

- **CTS in burning plasmas**: Why and how?
- **Possible measurements** in ITER, DEMO, SPARC, STEP (+ JT60-SA)
- **Challenges and opportunities** with CTS in the burning-plasma era
- **Summary**



Collective Thomson scattering in burning plasmas: How and why?

Principle of CTS



Need:

$$\alpha_s = \frac{1}{|\mathbf{k}^\delta|\lambda_D} > 1 \;\rightarrow \text{microwaves}$$

High P_{probe} → gyrotrons

Possible measurements

$$g(u) = \int f(\mathbf{v})\delta\left(\frac{\mathbf{v}\cdot\mathbf{k}^\delta}{k^\delta} - u\right) d\mathbf{v}$$

- T_i, v_{tor}
- $f_{fast}(u = v_{1D})$
- For $\varphi \approx 90^o$: n_D/n_T, $n_{He\text{-}3}$, n_{imp}

for confined ions – spatially resolved.

Reactor relevance

- Versatility: Non-invasive monitoring of
  - fusion fuel
  - fusion products
  - kinetic profiles

  in plasma core
- No optical components, no enhanced background

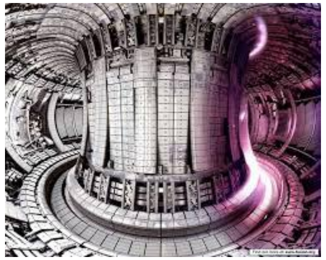
  [Rasmussen+ 2022 *EPS* O4.112]
- No reliance on NBI

CTS for ion dynamics & plasma–wave interactions at past/present devices

ASDEX-U

[Meo+ 2008 *RSI* **79** 10E501]

JET



[Bindslev+ 1999 *PRL* **83** 3206]

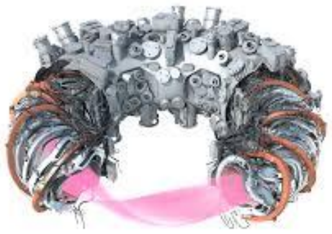
W7-AS

[Suvorov+ 1995 *PPCF* **37** 1207]

TEXTOR

[Bindslev+ 2006 *PRL* **97** 205005]

W7-X



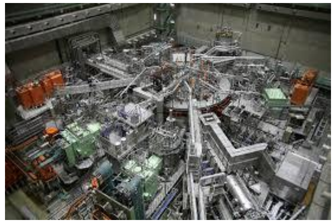
[Moseev+ 2019 *RSI* **90** 013503]

TFTR

[Machuzak+ 1995 *RSI* ***66*** 484]

FTU

[Tartari+ 2007 *RSI* **78** 043506]



LHD

[Kubo+ 2010 RSI ***81*** 10D535]

And soon: **TCV** [Meier+ in prep.]

Two main considerations for CTS diagnostic design optimization

Minimize background noise = mainly ECE → operate between/below ECE harmonics

Minimize refraction = sensitivity to plasma conditions → operate away from cutoffs

Procedure

Define freq. + geometry for a given set of plasma parameters $\boldsymbol{X}$

➡

Synthetic CTS spectra $\boldsymbol{Y}(\boldsymbol{X})$

➡

Add noise **σ**, including ECE with reflections [Rasmussen+ 2019 PPCF **61** 095002] + bremsstrahlung $P_{br} \propto n^2 T^{1/2}$

➡

Invert noisy spectra $\tilde{\boldsymbol{Y}}(\boldsymbol{X},\boldsymbol{\sigma})$ using realistic priors → $\tilde{\boldsymbol{X}}$

➡

Assess mean accuracy and precision on $\tilde{\boldsymbol{X}}$

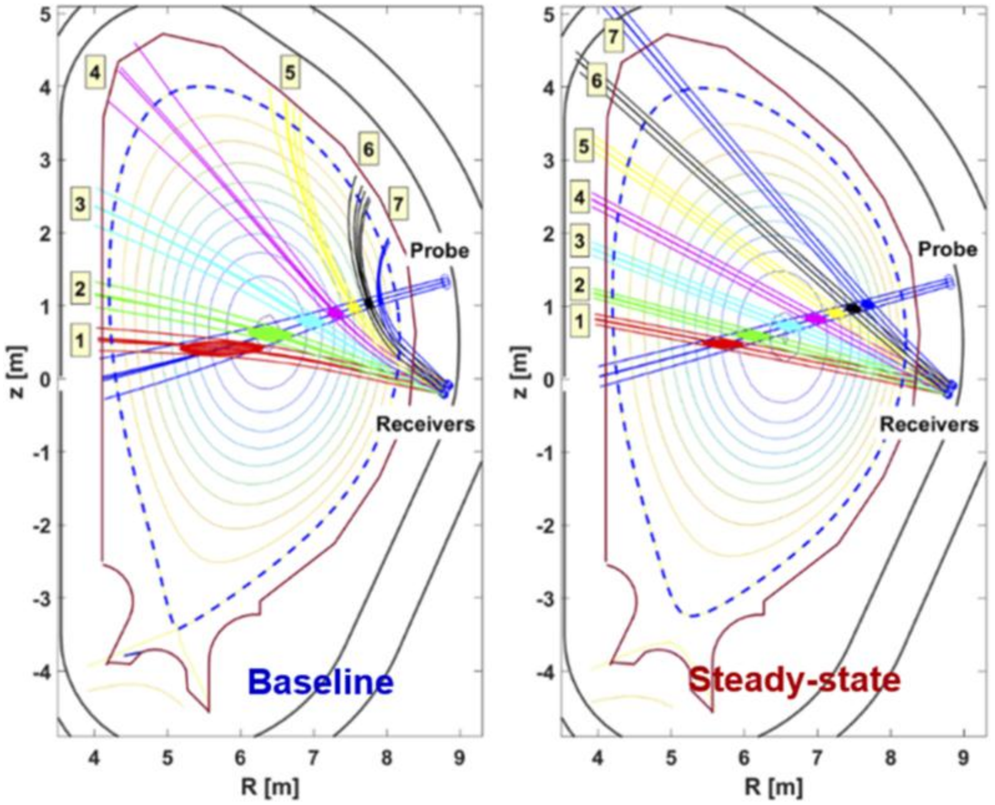
ITER CTS fully designed under contract with F4E

Goal: Contribute to measurements of density profiles and ”energy” spectra of

- Fusion alphas
- Fast p, D, T, ^{3}He from fusion or auxiliary heating

Measurement requirements: n_α to 20% at

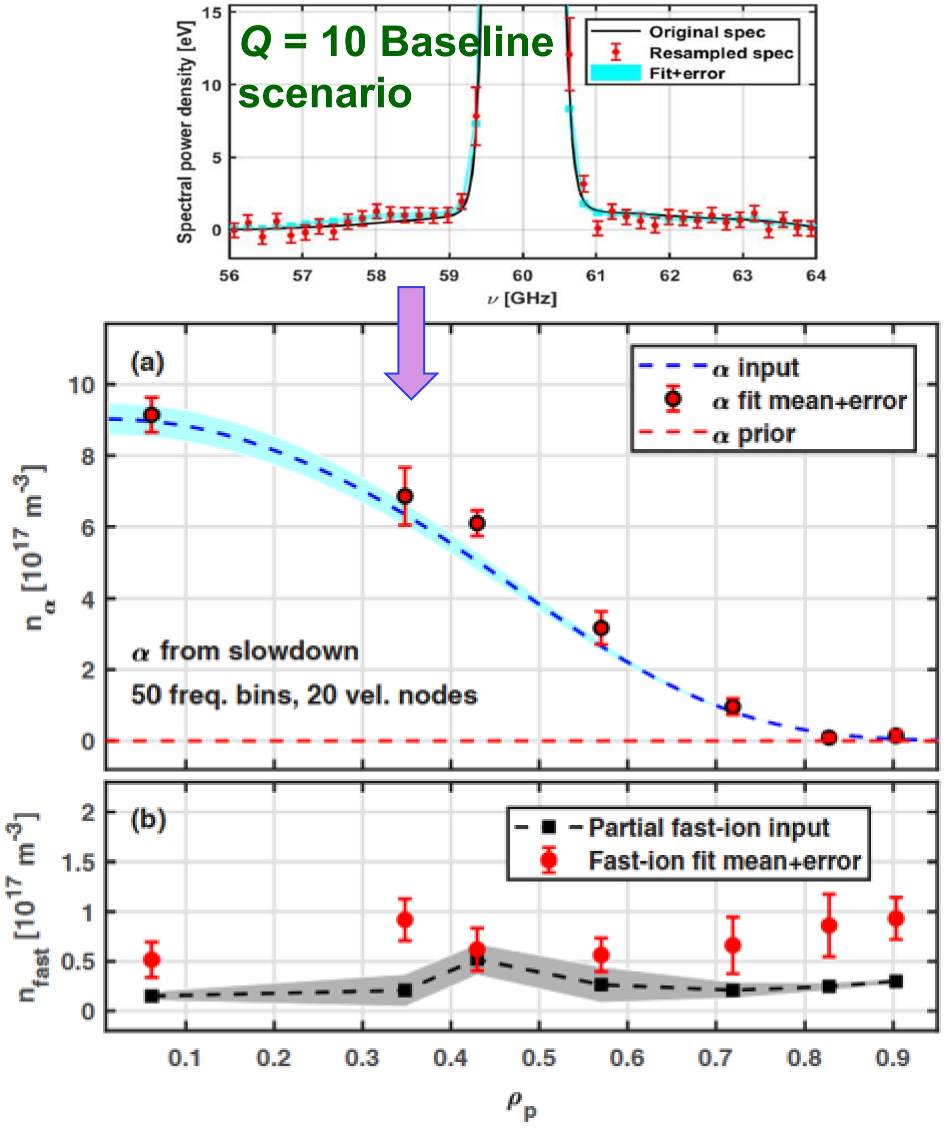
- Δt = 100 ms
- ΔR = 10–100 cm



Design: Subharmonic system, 60 GHz X-mode

[Korsholm+ 2022 *RSI* **93** 103539]; see also [Orsitto & Giruzzi 1997 *RSI* **68** 686]

ITER CTS fusion alpha measurements meet the requirements



Inferred accuracy on n_α: 10–15% at Δt = 100 ms

$n_\alpha(\rho, u)$ for monitoring of

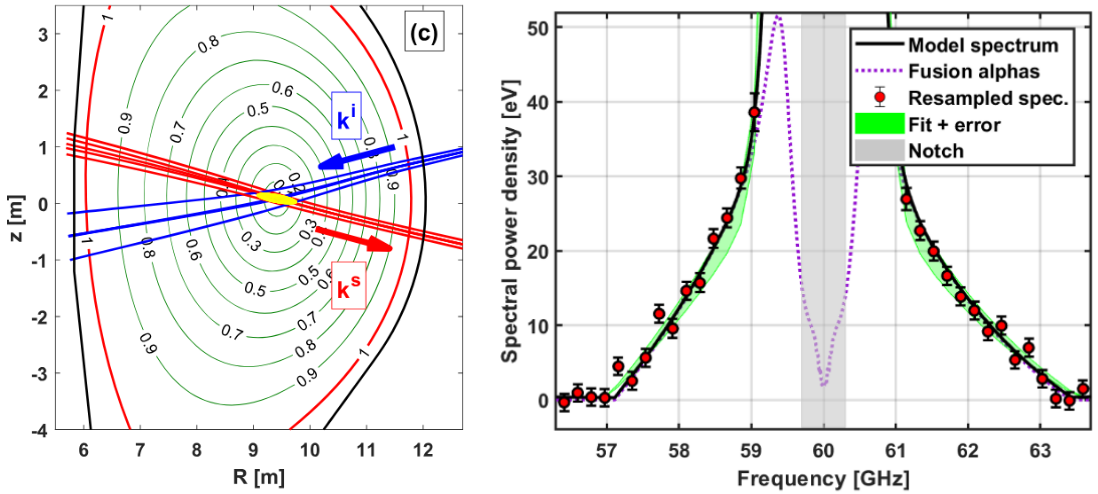
- $S_{\rm fus} = 3E_\alpha n_\alpha [\tau_{\rm SD} \ln(1 + ({}^{v_{\rm b}}/_{v_{\rm c}})^3)\,]^{-1}$ [W/m³]
- α transport in real- and velocity space → interactions with MHD modes

Simultaneous monitoring of other MeV ions is feasible (e.g. $n_{\rm D,NBI}$ to < 15%)

[Rasmussen+ 2019 *NF* **59** 096051]

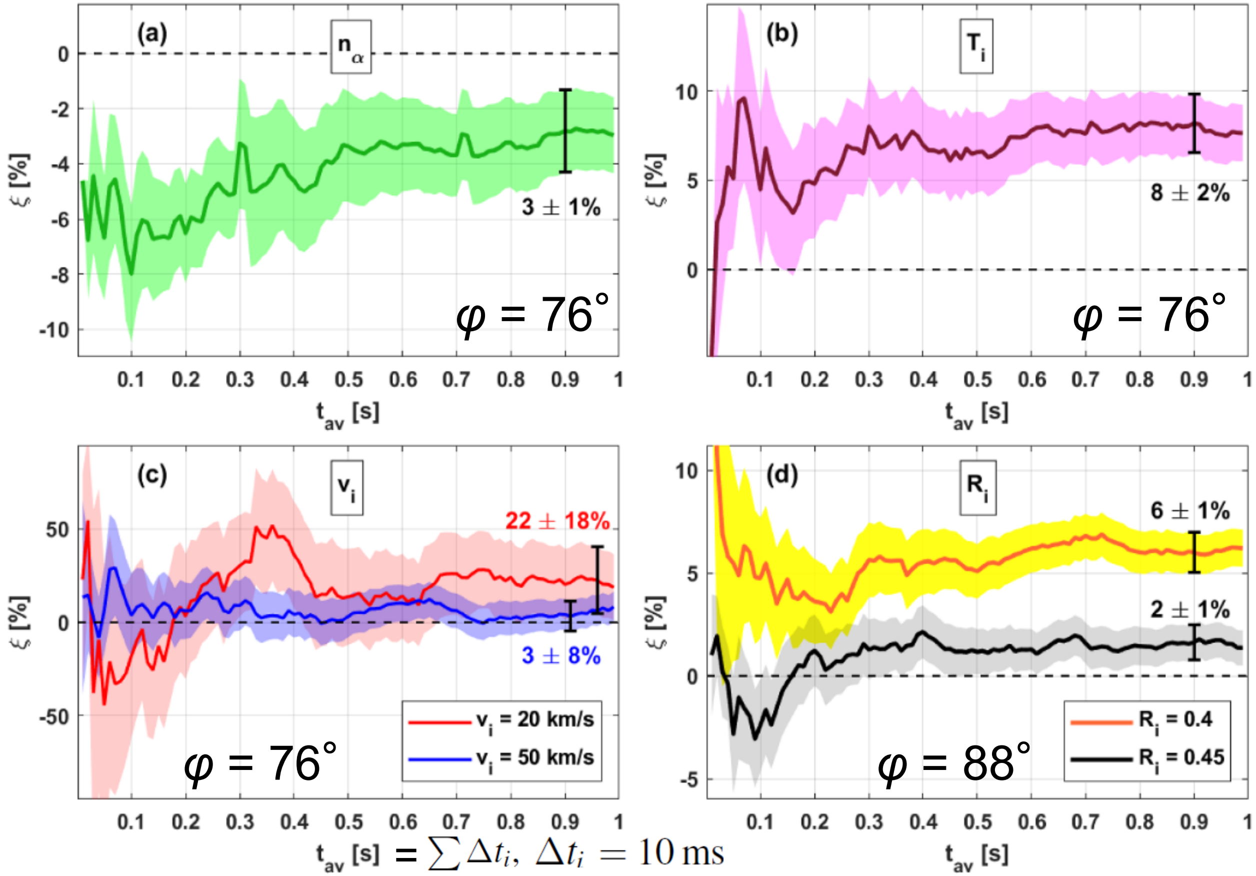
EU-DEMO "2019 G1 baseline" configuration: Core CTS also feasible

ITER-like setup:
60 GHz subharmonic X-mode



[Rasmussen & Korsholm 2024 *NF* **64** 046003]

$\xi = (\langle p_{\rm fit}\rangle - p_{\rm true})/p_{\rm true}$:

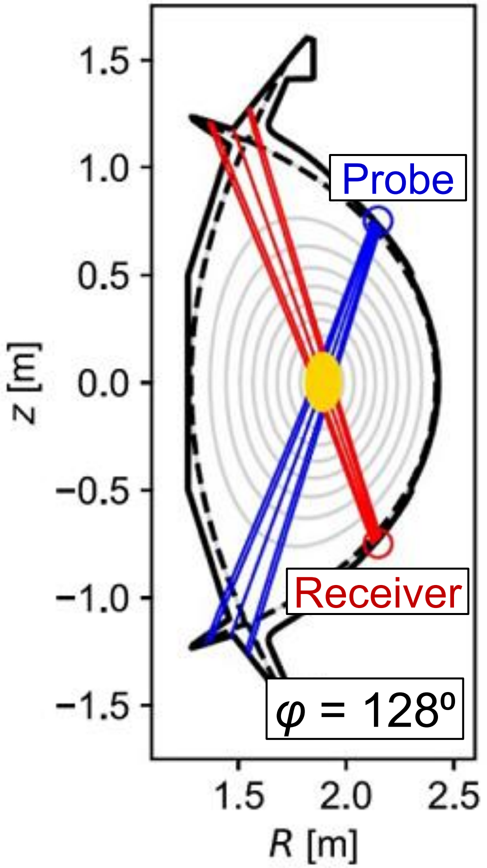


t_{av} [s] $= \sum \Delta t_i, \ \Delta t_i = 10$ ms

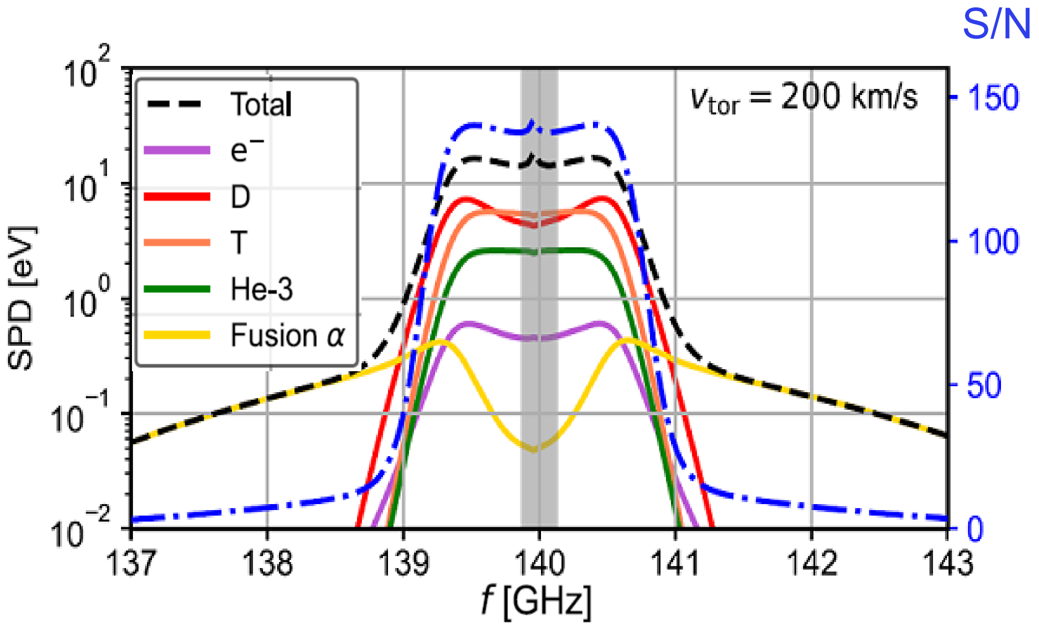
For the 2024 DEMO low aspect ratio config: See talk by J. Flocken on Friday

CTS in an ICRH-only device: SPARC as a promising case

SPARC operation 2027 → short timeline → use available gyrotron tech. → 140 GHz X-mode



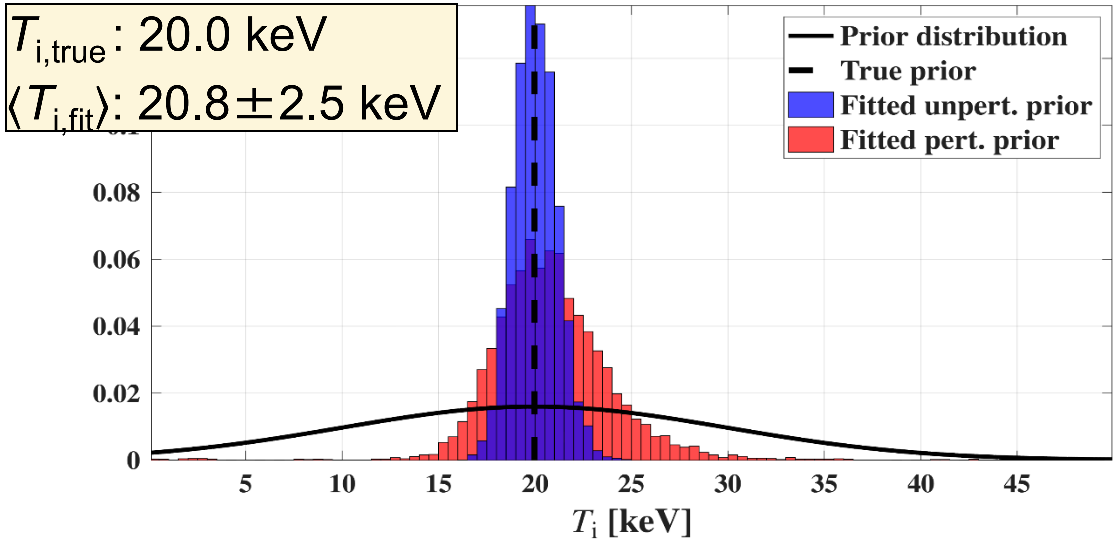
- Q = 11 Primary Reference Discharge
- $B_t \approx 12.5$ T → distance to
  - X_L cutoff ≈ 60 GHz
  - n = 1 ECR ≳ 250 GHz

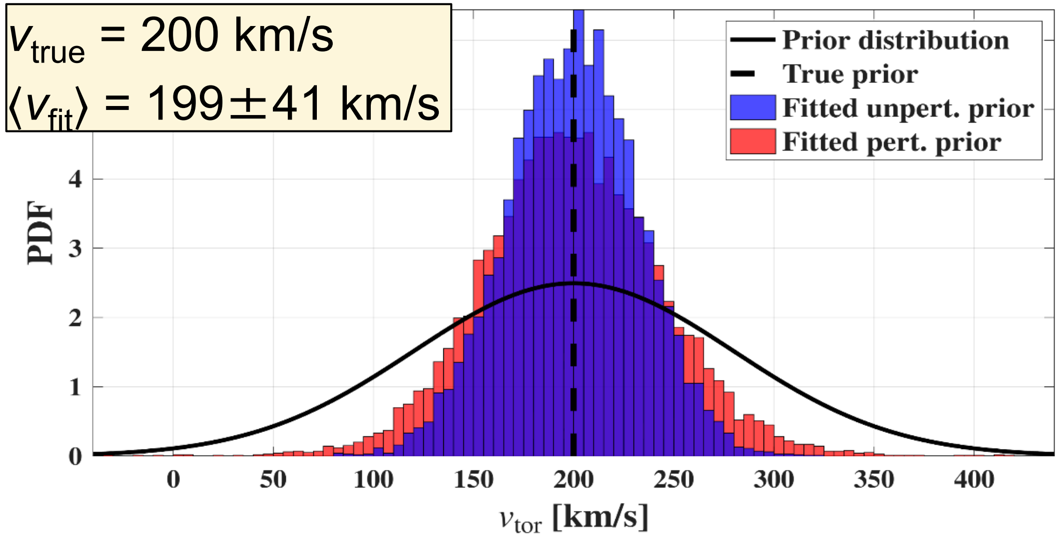


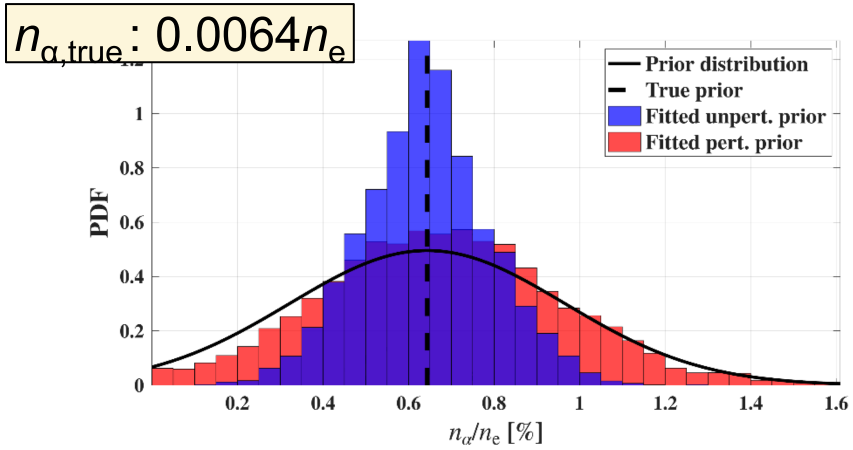
- No refraction, CTS background noise dominated by bremsstrahung

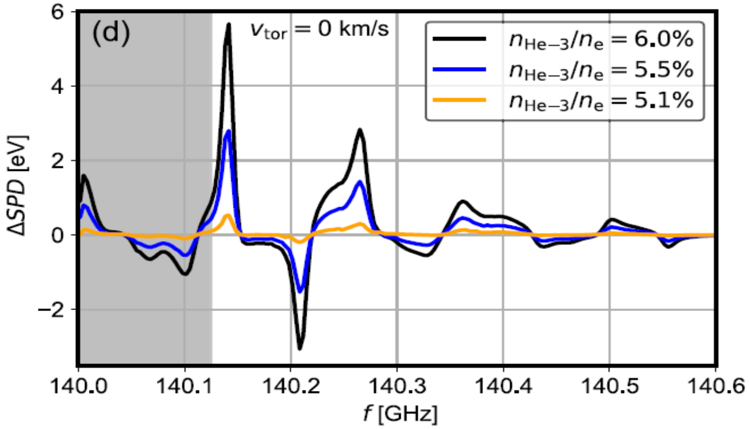
[Mentz-Jørgensen+ 2025 *NF* **65** 046028]

Preliminary results: Good reconstruction of bulk-ion properties









Variations in He-3 content (default: 5%)

Work by M. Mentz-Jørgensen

CTS in a spherical tokamak? The (challenging) case for STEP CTS

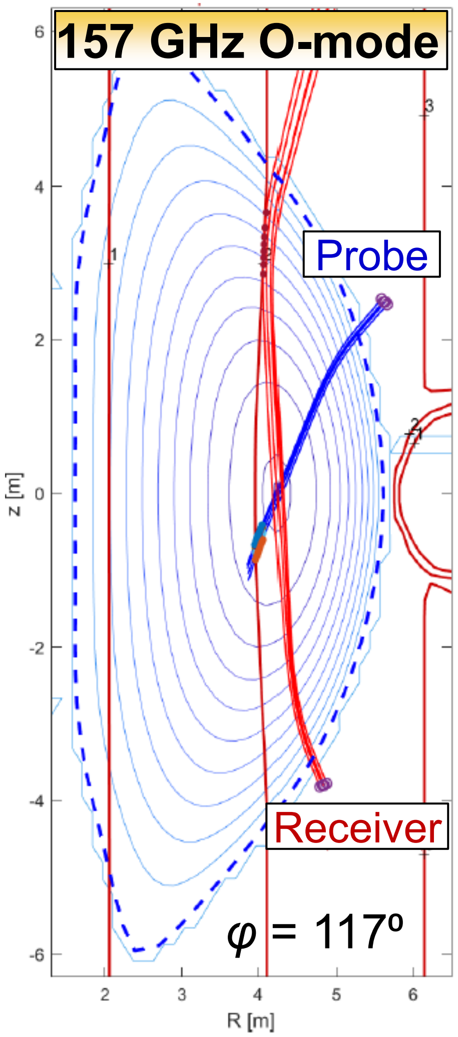
STEP ”SPP-001” configuration

Challenges:

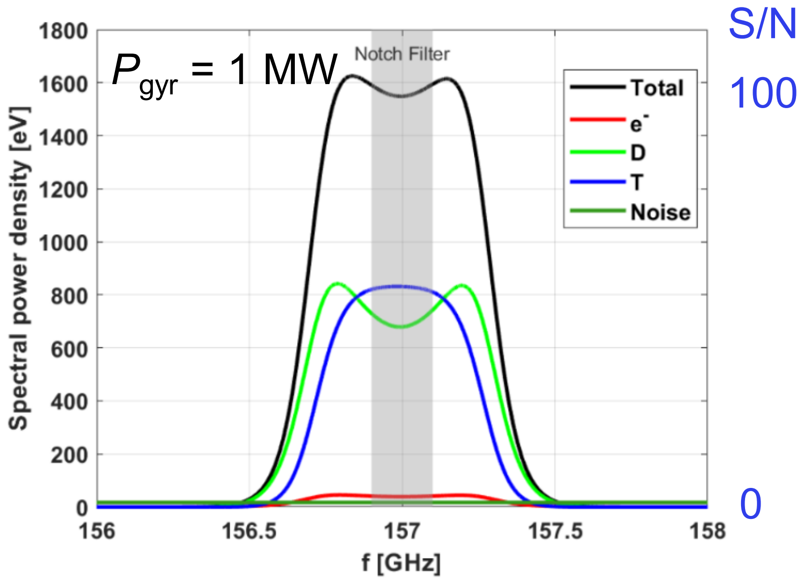
- $n_{e,0} \approx 2 \times 10^{20}$ m^{-3} → high cutoff freq.
- Low B_t = 3.2 T and low $A = R/a \approx 1.8$ → ECE harmonic overlap

Subharmonic setup not an option + near-vertical geometry required

Note: Port locations not yet defined



JETTO 2023 equil. (without fusion alphas)



2025: New ”SPP-002” config:
R: 3.6 → 4.3 m, $n_{e,0}$ → 1.3 $\times 10^{20}$ m^{-3}

[Olde+ 2025 *EPS* 4P.275]

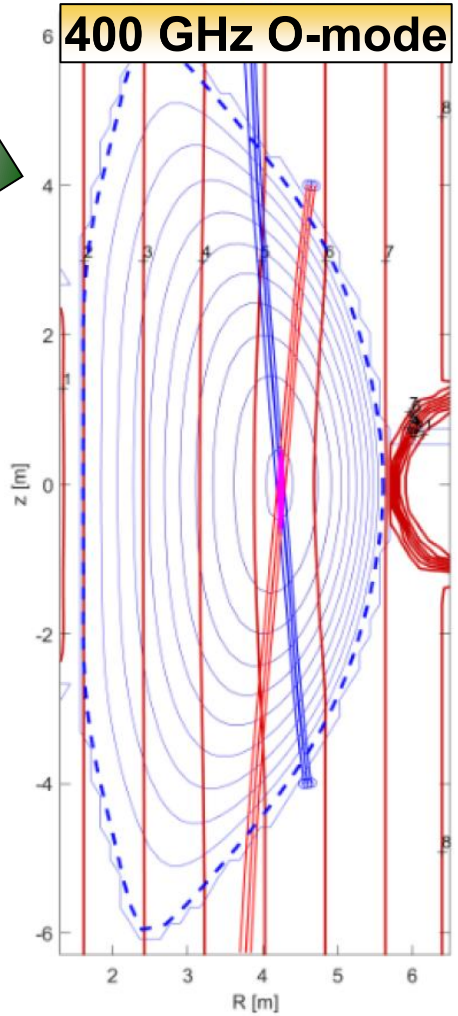
Work by V. Esposito + M. Bøtker-Rasmussen

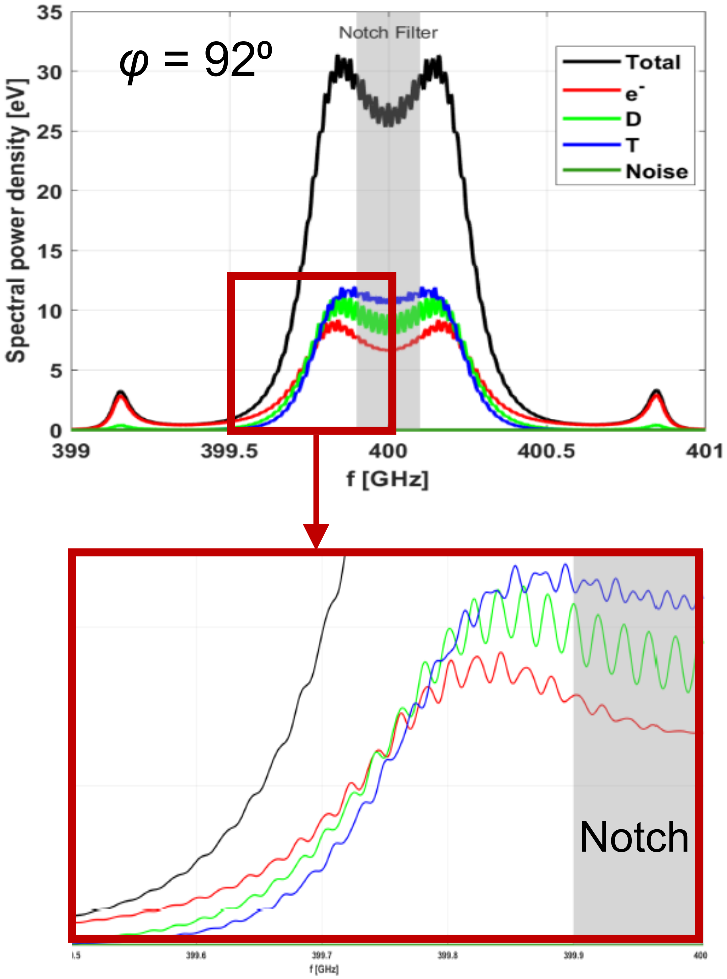
STEP: Possible alternatives available at ~sub-THz frequencies

- 400 GHz $P \approx 100$ kW gyrotron
  [Saito+ 2010 *J. Phys.: Conf. Ser.* **227** 012013;
  2019 *Plasma Fusion Res.* **14** 1406104]

- Vertical/toroidal laser-based ~1 THz setup

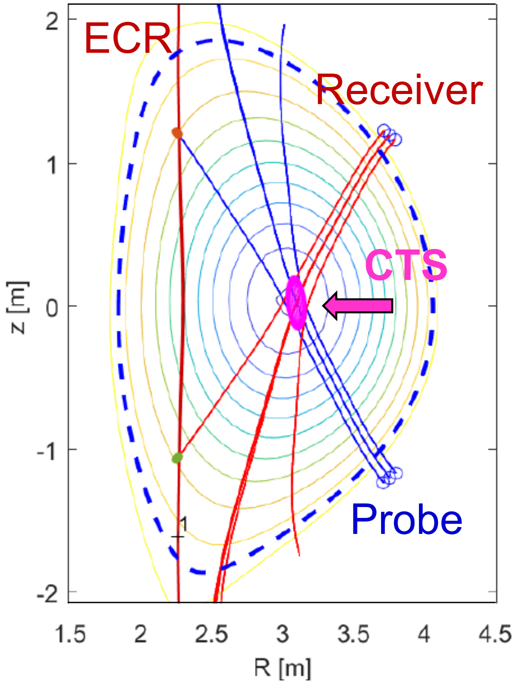
O_b [/m]	ρ	φ [°]	α_s	T_{rad} [keV]
68	0.00	88	4.1	0.5
49	0.03	132	7.7	0.01



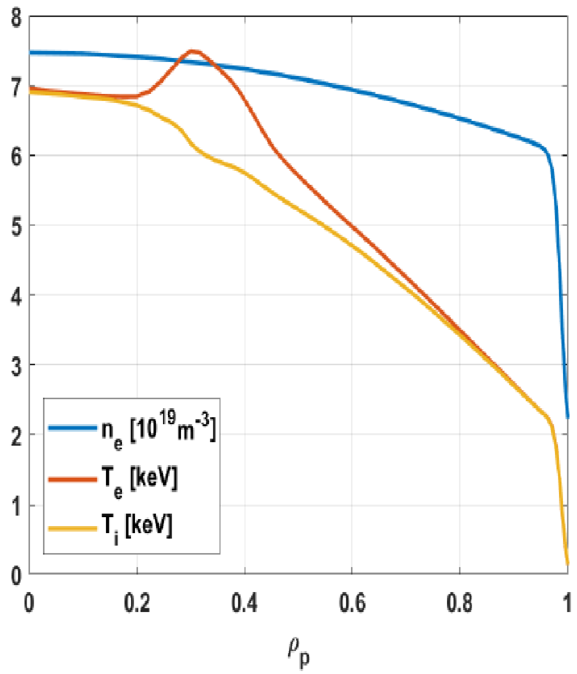


JT60-SA: Initial study confirms feasibility of fast-ion CTS

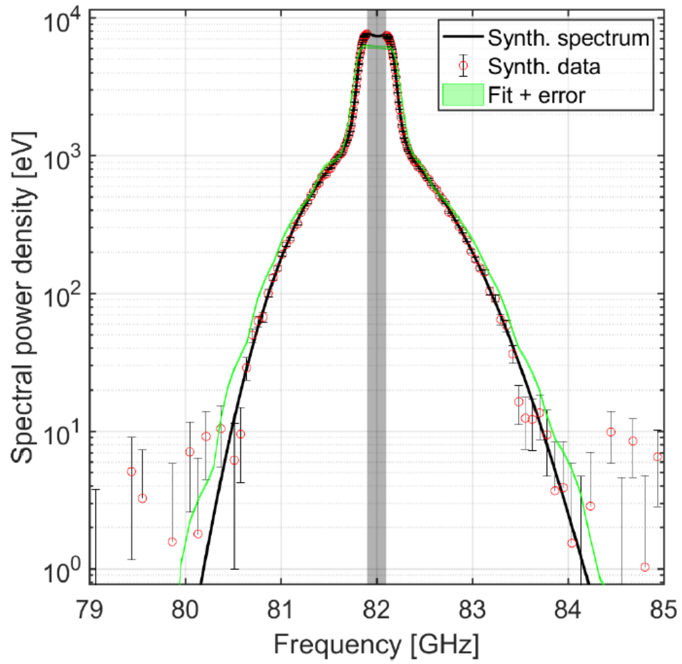
Potential implementation



EFIT BaselineScenarioOP2



$n_{fast} = n_{D,NBI}$ to ~10%, T_i to ~5%



82 GHz, O-mode: φ = 67º / 92º

Using existing ECRH infrastructure, port P-1, P-4, P-8, or P-11

But need more plasma equilibria for sensitivity study

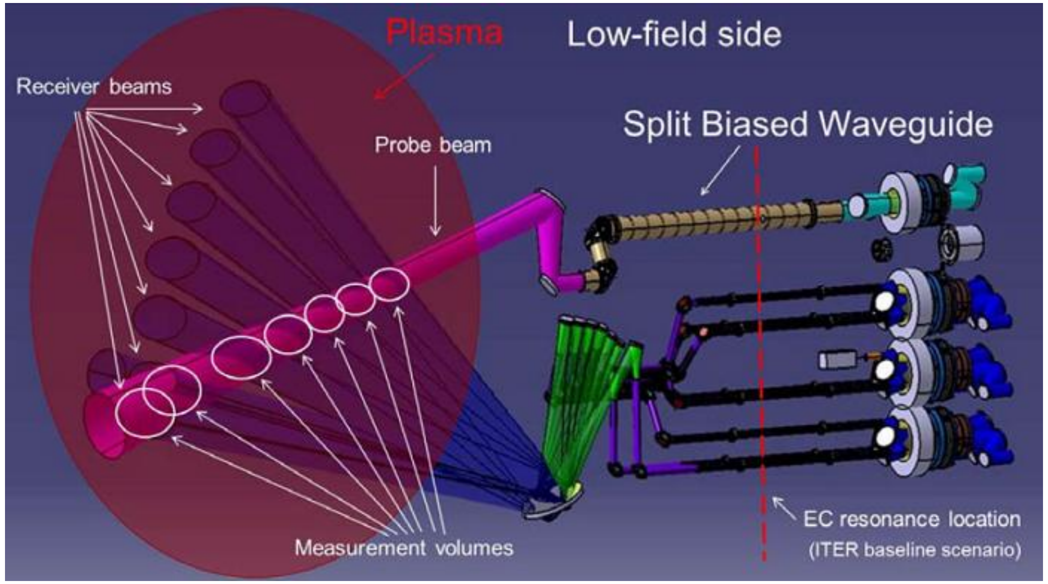
May require: 82 GHz → 110 GHz due to cutoff

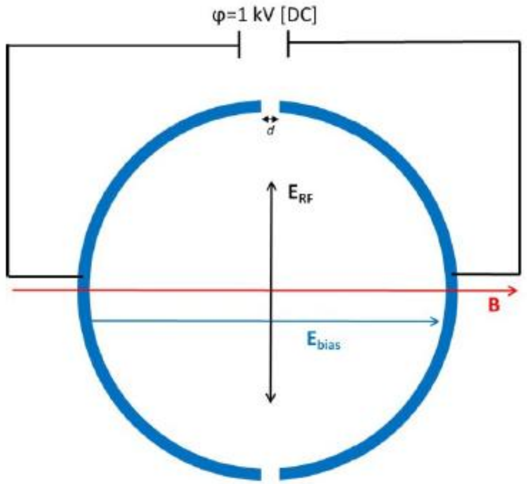
Work by E. A. Christensen

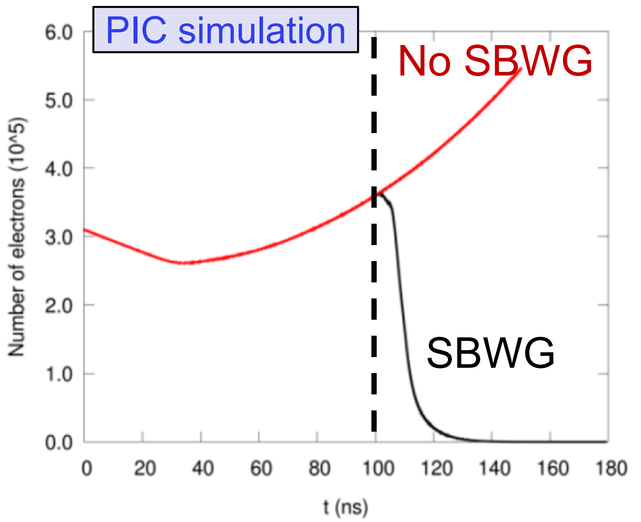
Operational considerations: Challenges in burning-plasma devices (1)

Risk of local breakdown:

ITER, DEMO, SPARC: Subharmonic setup, with n = 1 ECR location in gyrotron waveguide





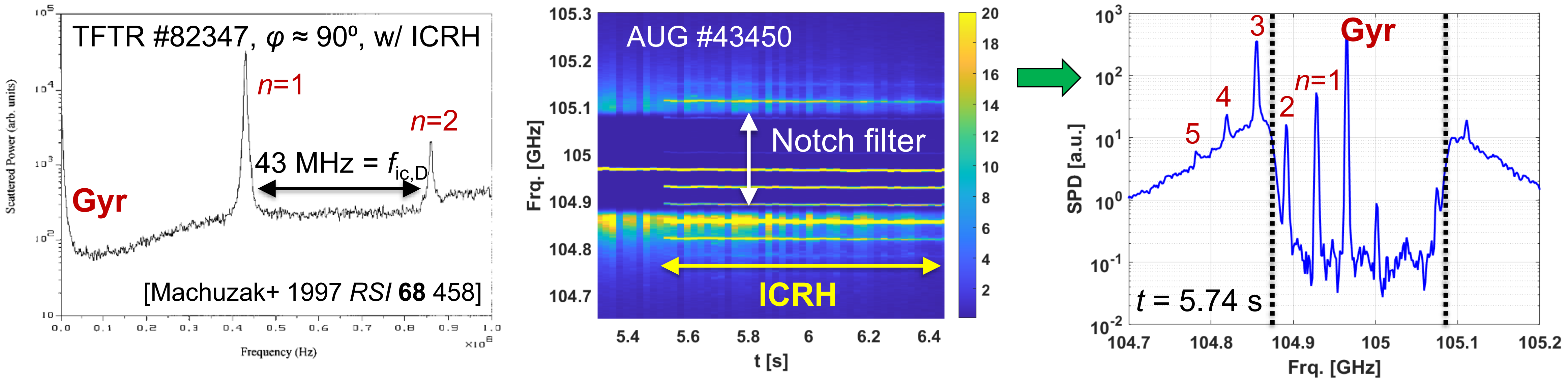


Planned mitigation at ITER: Split biased waveguide [Larsen+ 2019 *JINST* **14** C11009]

Operational considerations: Challenges in burning-plasma devices (2)

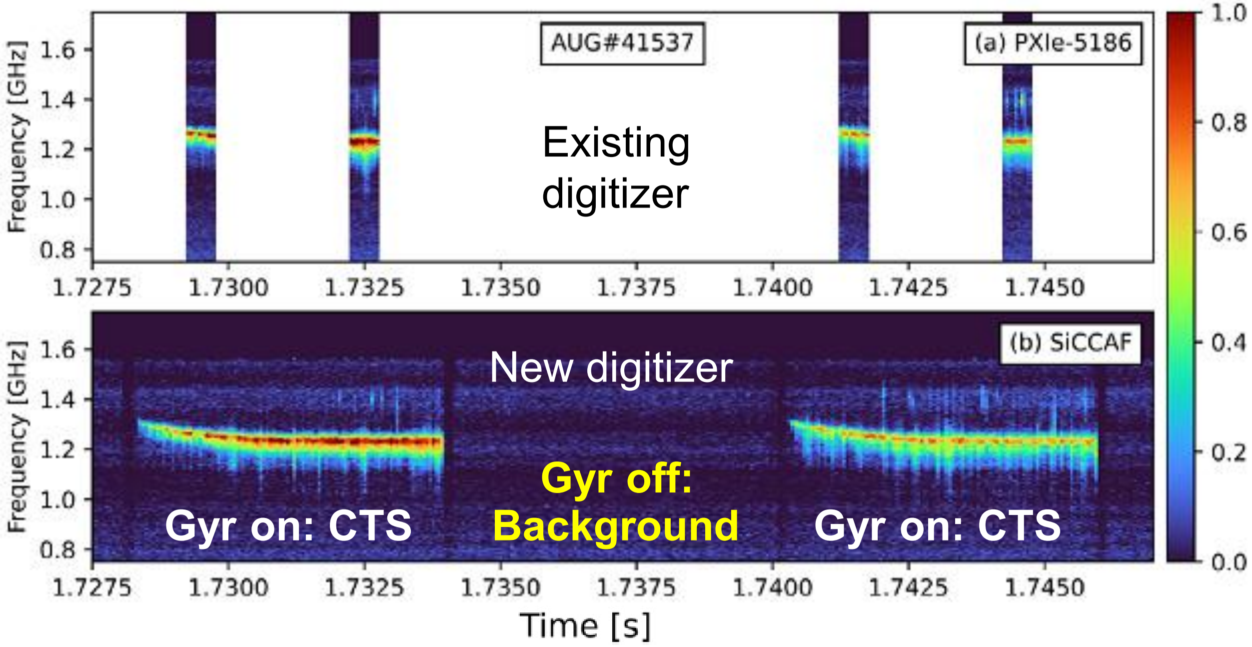
Induced emission by MeV ions (for $\varphi \approx 90^o$) or non-linear gyrotron–ICRH wave mixing

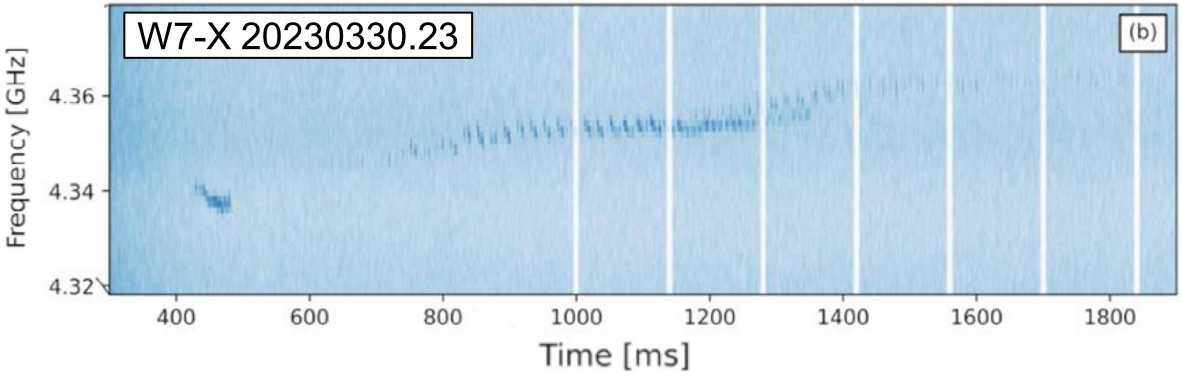
[TFTR: Machuzak+ 1997 *RSI* **68** 458], [TEXTOR: Woskov+ 2006 *RSI* **77** 10E524], [AUG: Meo+ 2010 *J. Phys. Conf. Ser.* **227** 01201]



Possible mitigation: Passive CTS receiver [Nielsen+ 2015 *PPCF* **57** 035009], probe gyrotron power modulation [Verdier+ 2025 *RSI* **96** 043513] , tunable notch filters [Acar+ 2016 *Int. J. Microw. Wirel. Tech.* **8** 567]

Promising prospects for near-continuous CTS measurements



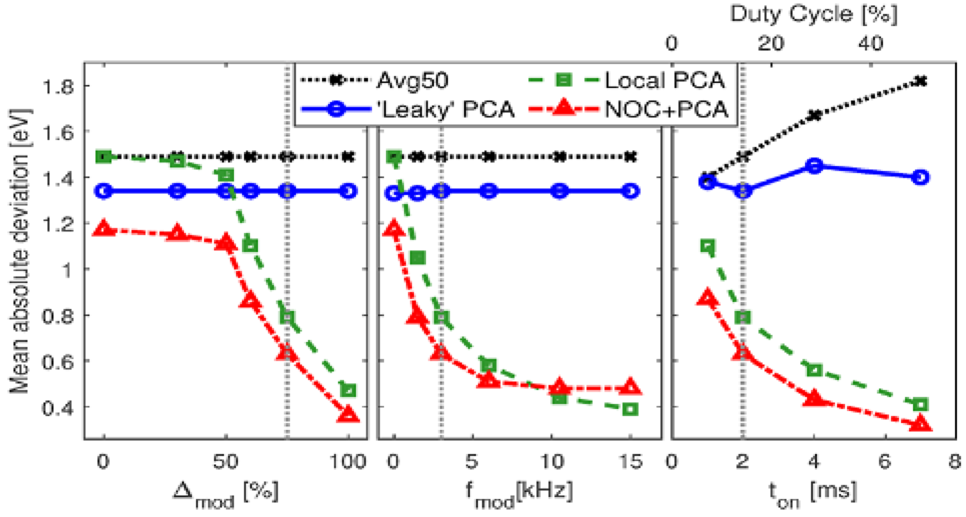


FPGA-based continuous fast digitizers now becoming available

[Verdier+ 2024 *FED* **206** 114597]

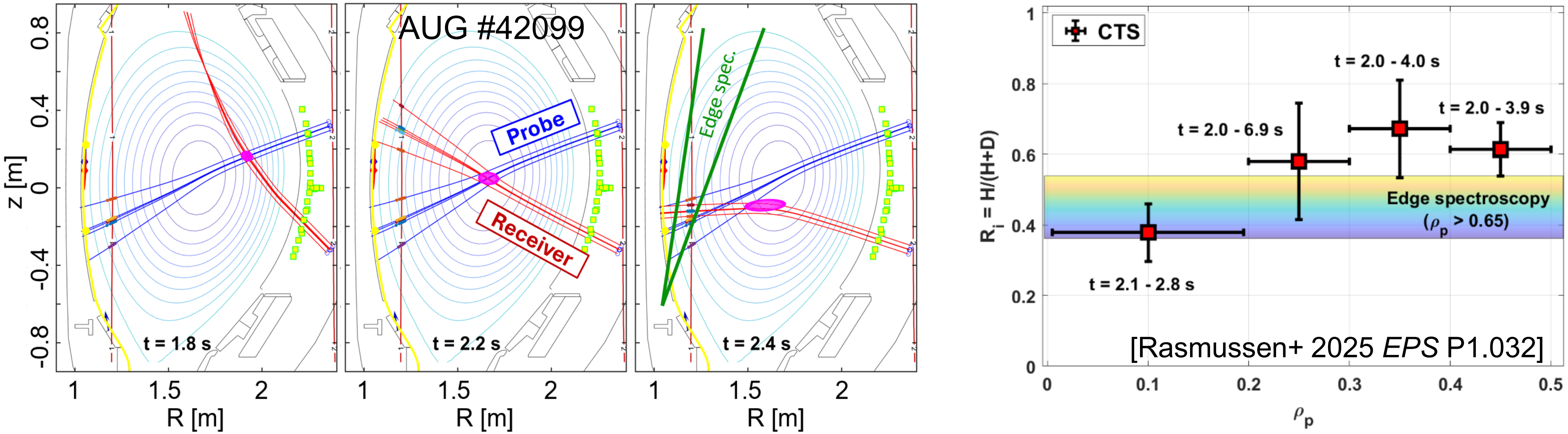
Novel CTS background techniques also allow longer acquisition pulses

[Verdier+ 2025 *RSI* **96** 043513]



Opportunities for CTS-based real-time control of burning plasmas

ASDEX-U CTS: First core measurements of n_H/n_D in a purely ECRH-heated plasma:



- Preliminary results based on a multilayer perceptron neural network
- Prospects towards rapid inference using continuous FPGA-based digitizers ⟶ **real-time control** [Verdier+ 2024 *FED* **206** 114597]

See also [Van den Berg+ 2018 *RSI* **89** 083507; Stylianidis 2019 MSc Thesis TU/e; Nishiura+ 2020 *JINST* **15** C01002; Zhang+ 2024 *RSI* **95** 093542]

Overview: CTS can monitor key physics/operational parameters

Across burning-plasma devices, CTS can contribute to monitoring

- P_{fus} and alpha transport through measurements of $n_{\alpha}(\rho, v_{1D})$
- Fast D, T, H, …distribution functions (from fusion or auxiliary heating)
- Core ion heat transport (T_i) and toroidal rotation (instabilities, H-mode access)
- Fuel-ion ratios → optimization of P_{fus} + pellet fuelling scheme (burn control)
- He minority concentrations (He ash, optimization of auxiliary heating)
- ELMs (for mitigation / pellet pacing) [Verdier+ 2025 *RSI* **96** 043513]

on timescales $t < 0.1\tau_E \sim 0.1\tau_{slowdown,\alpha}$ (ITER/DEMO)

Summary and outlook

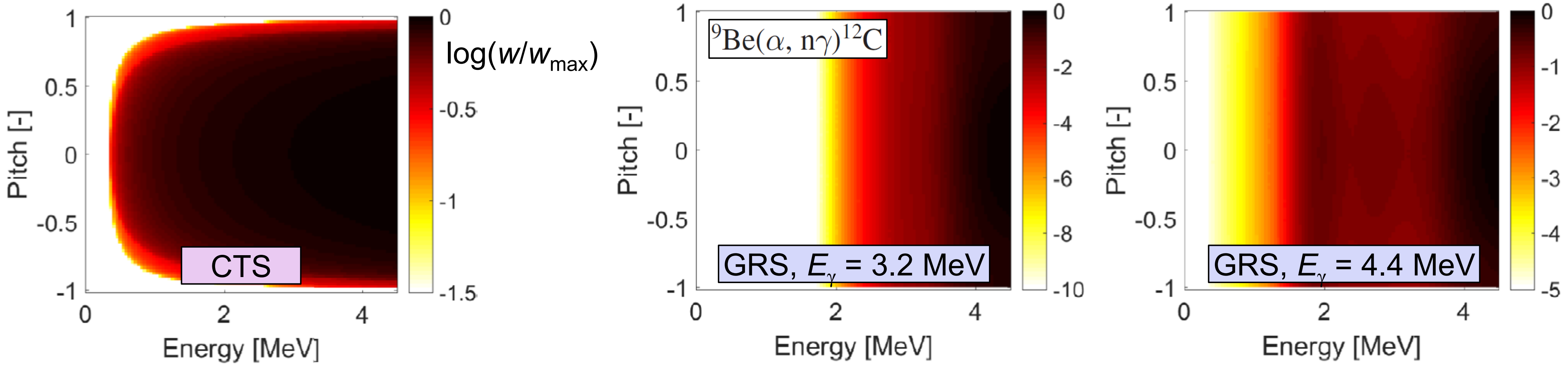
- **CTS can play pivotal role in monitoring key plasma parameters in burning plasmas → optimization of machine performance and safety**
- **Diagnostic being built for ITER, useful setups also feasible at DEMO, SPARC, JT60-SA – and perhaps STEP**
- **Ongoing soft- and hardware developments → promising prospects for using CTS for continuous real-time control of burning plasmas**

Backup

The fusion alpha *energy* distribution is not directly accessible by CTS

No single-view diagnostic can directly measure *E* of confined fusion alphas

Weight functions *w*: $S = \int\int w f dv_{\|} dv_{\perp}$ = diagnostic **observation regions**:



- CTS the only diagnostic to measure ITER fusion alphas at **all** *E* (also with W wall)
- α energy spectrum inferable if assuming e.g. *isotropy* in velocity space

[Salewski+ 2018 *NF* **58** 096019; 2025 *NF* submitted], [Ciurlino+ 2025 *EPS* 2P.126]